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NOx Emission Factors for Wood-Fired Boilers

TRW Environmental Engineering Div, Durham, NC

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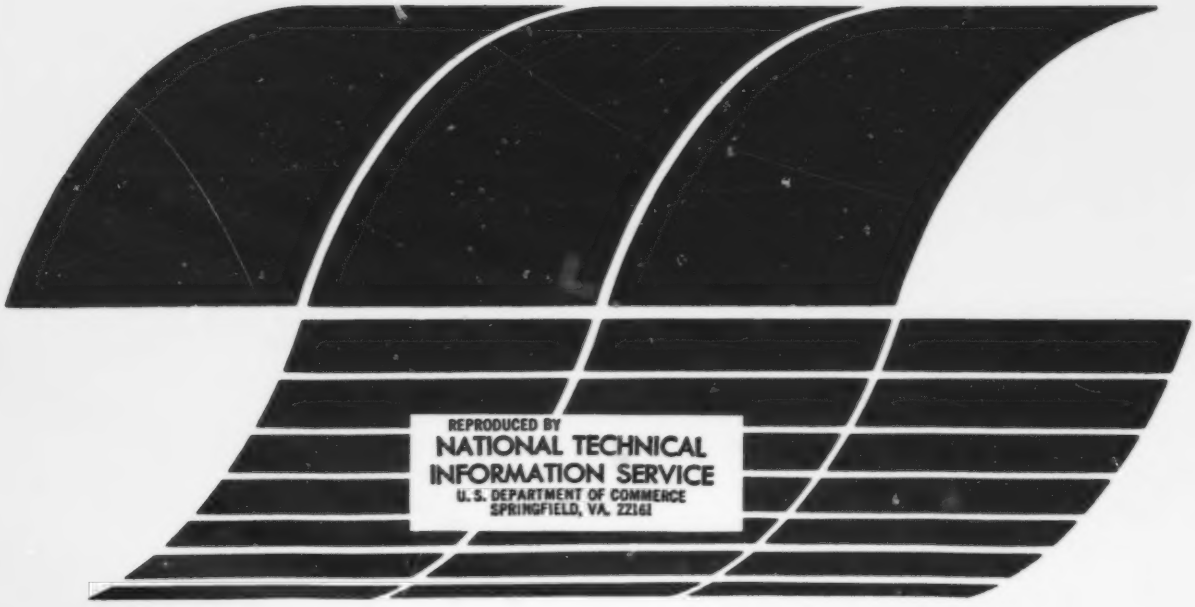

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16. ABSTRACT The report gives results of a review of NOx emission data from 14 wood-fired boilers. Types of wood used as fuel included sawdust, chips, shavings, edgings, bark, and other processing residues. Boilers tested ranged in size from 1.5 to 67 MW (4,500 to 200,000 lb steam/hr). The major finding was that wood-fired boilers emit considerably less NOx (on an energy basis) than fossil fueled boilers of comparable size, in spite of the fact that most wood-fired boilers operate with high levels of excess air, a practice normally associated with increased NOx emissions. Average emission factors were 0.3 g NOx per kg fuel for boilers less than 10 MW, and 1.6 g NOx per kg fuel for boilers greater than 10 MW.

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NO_x Emission Factors for Wood-Fired Boilers

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ABSTRACT

NO_x emission data from fourteen (14) wood-fired boilers have been reviewed. Types of wood fuel being fired included sawdust, chips, shavings, edgings, bark, and various other processing residues. Boilers tested ranged in size from 1.5 to 67 MW (4 500 to 200 000 lb stream/hr). The major finding was that wood-fired boilers emit considerably less NO_x (on an energy basis) than fossil fuel boilers of comparable size. This is interesting because most wood-fired boilers operate with high levels of excess air, a practice which normally is associated with increased NO_x emissions. Average emission factors were 0.3g NO_x per kg fuel for boilers less than 10 MW, and 1.6g NO_x per kg fuel for boilers greater than 10 MW.

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SECTION 1

INTRODUCTION

During this period of energy shortages and rapidly rising fuel costs, alternate fuels for all types of boilers are receiving increased interest. The use of wood processing residues (e.g., bark, sawdust, and shavings) is being emphasized by the U.S. Department of Energy (DOE) in a Wood Combustion Commercialization Program. This is, by no means, a new technology. At present, wood combustion in industrial boilers produces approximately 0.4 Quads of energy per year. Due to the abundance of wood processing residues, it is the goal of the DOE to expand its use throughout the country.

As with the combustion of any type of fuel, the environmental impact associated with boiler emissions must be investigated. There is, at present, however, a paucity of data pertaining to wood-fired boiler emissions. The purpose of this report is to assist the U.S. Environmental Protection Agency in ascertaining the magnitude of NO_x emissions from such boilers and developing applicable emission factors.

SECTION 2

METHODOLOGY

Source test data were obtained from eleven (11) industrial boilers using some type of wood as the sole fuel and three (3) boilers using wood in conjunction with oil, coal, or natural gas. The types of wood being used as fuel were primarily wood processing residues and included sawdust, chips, shavings, edgings, bark, and various other scraps. The following information was extracted from the source test data:

Size of Boiler

Manufacturer

Type of Fuel

Fuel Feed Rate

Heat Content of Fuel

Temperature of Fire Box

Percent Excess Air

NOx Concentration in Exhaust Gas

Exhaust Flow Rate

Exhaust Temperature

Type of Control Device

Type of Sampling Procedure.

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Not all of the information was available for each boiler tested, and for summary purposes, estimates were made in some cases. Boilers tested ranged in size from 1.5 to 67 MW (4,450 to 200,000 lb steam/hour). No plant larger than 17.0 MW (59,600 lb steam/hour) which was fired on wood alone was tested.

On the basis of the collected data, NO_x emission rates were calculated in the units of g/kg fuel, lb/ton fuel, mg/10^6 joule, and lb/10^6 Btu. The boilers were then separated into the following three categories:

<10.0 MW (29,670 lb steam/hour)

≥10.0 MW

>10.0 MW (wood as supplement to coal).

Emission factors were calculated for these three categories on the basis of the mean emission rates of those boilers tested in each category.

Of the fourteen (14) boilers tested, six (6) were small industrial boilers located in Vermont and studied by the EPA Region I.[1] Two of the boilers in which wood was used on a co-firing basis were tested by KVB, Inc. for EPA's Industrial Environmental Research Laboratory at Research Triangle Park.[2] One test was performed on a small power generation plant in Vermont.[3] The remaining five (5) boilers were tested by TRW for the EPA.[4] Table 2-1 describes each boiler for which data are presented and the source from which it came.

The results of all tests and calculations are presented in Section 3 and Appendix A of this report.

TABLE 2-1. TEST DATA SOURCES

Boiler	Size	Fuel Type	Data Source
A	1.5 MW (4,450 lb steam/hr)	Shavings	Reference 1
B	2.5 MW (7,420 lb stea/hr)	Shavings/Sawdust	Reference 1
C	2.0 MW (5,930 lb steam/hr)	Shavings/Sawdust	Reference 1
D	2.5 MW (7,420 lb steam/hr)	Edgings	Reference 1
E	2.9 MW (8,600 lb steam/hr)	Scraps	Reference 1
F	1.5 MW (4,450 lb steam/hr)	Shavings/Sawdust	Reference 1
G	1.5 MW (4,450 lb steam/hr)	Pressed Sawdust	Reference 4
H	11.6 MW (34,000 lb steam/hr)	Pine Wastewood	Reference 4
I	16.8 MW (50,000 lb steam/hr)	Sawdust	Reference 4
J	6.6 MW (19,580 lb steam/hr)	Sawdust	Reference 4
K	5.7 MW (17,000 lb steam/hr)	Wastewood	Reference 4
L	33.0 MW (100,000 lb steam/hr)	80% Chips/20% Oil	Reference 3
M	67.0 MW (200,000 lb steam/hr)	85% Bark/15% Gas	Reference 2
N	33.0 MW (100,000 lb steam/hr)	20% Bark/80% Coal	Reference 2

SECTION 3

RESULTS

NOx emission rates remained relatively constant within boiler size categories. As boilers increase in size, however, the emission rates for NO_x also increase. There is, unfortunately, a shortage of information available on wood fired boilers larger than 17 MW (50,600 lb steam/hour).

Presented in Table 3-1 is a summary of the emission rates calculated for all boilers involved in the study. Expanded information on each boiler can be found in Appendix A. Sampling was accomplished using either continuous measurement with a chemiluminescence analyzer or by grab sample by EPA Measurement Method 7. In each case, exhaust flow measurements were made in accordance with EPA Method 2. A review of the test and calibration procedures utilized indicates that the tests were carried out properly and the data are reliable.

The correlation of emission rates with respect to boiler size is shown in Figure 3-1. From this, it can be seen that a definite relationship exists and, on that basis, it was decided that two emission factors would be developed with 10 MW (29,670 lb steam/hour) serving as the dividing point. Emission rates for the boilers smaller than 10 MW are remarkably similar as are their operating parameters. These boilers operate with an average of more than 300% excess air. In addition, fire

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box temperatures are generally in the range of 1000 to 1100°C (1832 to 2012°F). The larger boilers (>10 MW) exhibit less consistency in operating parameters and emission rates. The excess air usage ranges from 62 to 155% and the fire box temperatures are unknown.

An interesting phenomenon discovered during this study involves the relationship between emission rates and excess air consumption. Figure 3-2 depicts this relationship. For conventional fossil fuel fired boilers, NO_x emissions generally increase with an increase in excess air. This study revealed that for wood-fired boilers, the opposite relationship exists. This can be explained by the fact that the high levels of excess air decrease the fire box temperature, thereby decreasing the rate of formation of thermal NO_x. Thermal NO_x refers to NO_x formed by the oxidation of atmospheric nitrogen in the combustion air. It must be noted that the data presented in Figure 3-2 cover a variety of sizes of boilers. Studies should be conducted, therefore, which hold the boiler size constant and vary the excess air usage while monitoring NO_x emissions.

All emission factors are presented in Table 3-2. These emission factors are based on the test data from those plants in each size category. Most of the large wood-fired boilers are co-fired with a conventional fossil fuel. Although boilers in which wood is the primary fuel are the focus of this study, emissions data from these co-fired systems were included in the development of emission factors. A separate emission factor was developed for boilers in which wood is used as a minor supplement to coal only.

TABLE 3-1. EMISSIONS SUMMARY

Boiler	Boiler Size (MW)	Emission Factors	
		g NO_x/kg Fuel	mg $NO_x/10^6$ joule
A	1.5	0.10	5.0
B	2.5	0.10	6.0
C	2.0	0.10	5.0
D	2.5	0.75	38.0
E	2.9	0.10	6.0
F	1.5	0.04	2.0
G	NA (1.5)*	0.04	2.0
H	11.6	1.20	60.0
I	16.8	1.06	55.0
J	6.6	0.09	5.0
K	5.7	0.27	14.2
L (20% Fuel Oil)	33.0	0.80	50.9
M (15% Natural Gas)	67.0	NA (3.00)*	124.0
N (80% Coal)	33.0	4.04	168.0

* Estimated

TABLE 3-2. NO_x EMISSION FACTORS

Boiler Size	g NO_x/kg Fuel	mg NO_x/10^6 joule
<10.0 MW	0.30	9.0
≥10.0 MW	1.60	70.0
>10.0 MW*	4.00	170.0

* Wood used as supplement to coal only.

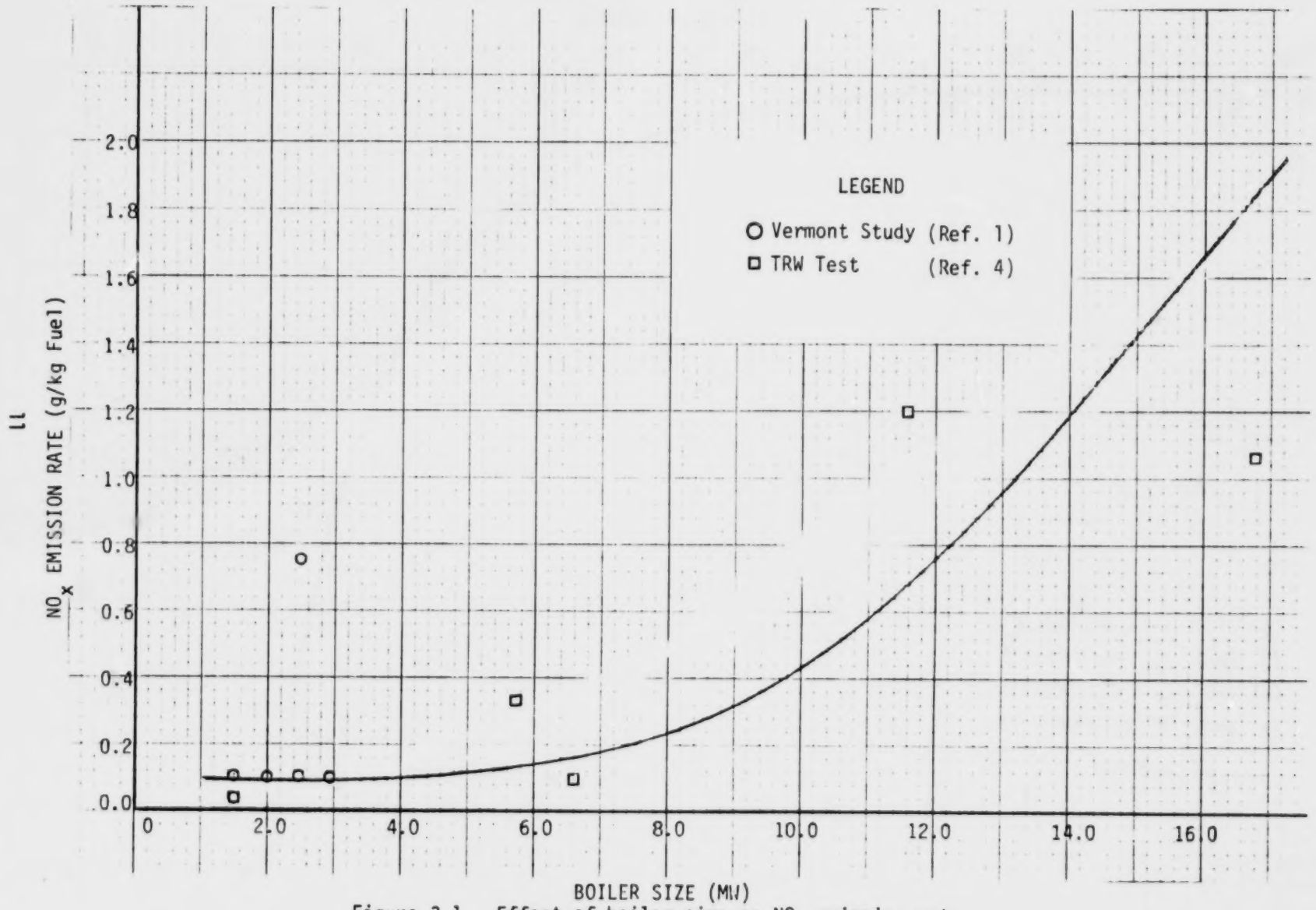

Figure 3-1. Effect of boiler size on NO_x emission rate.

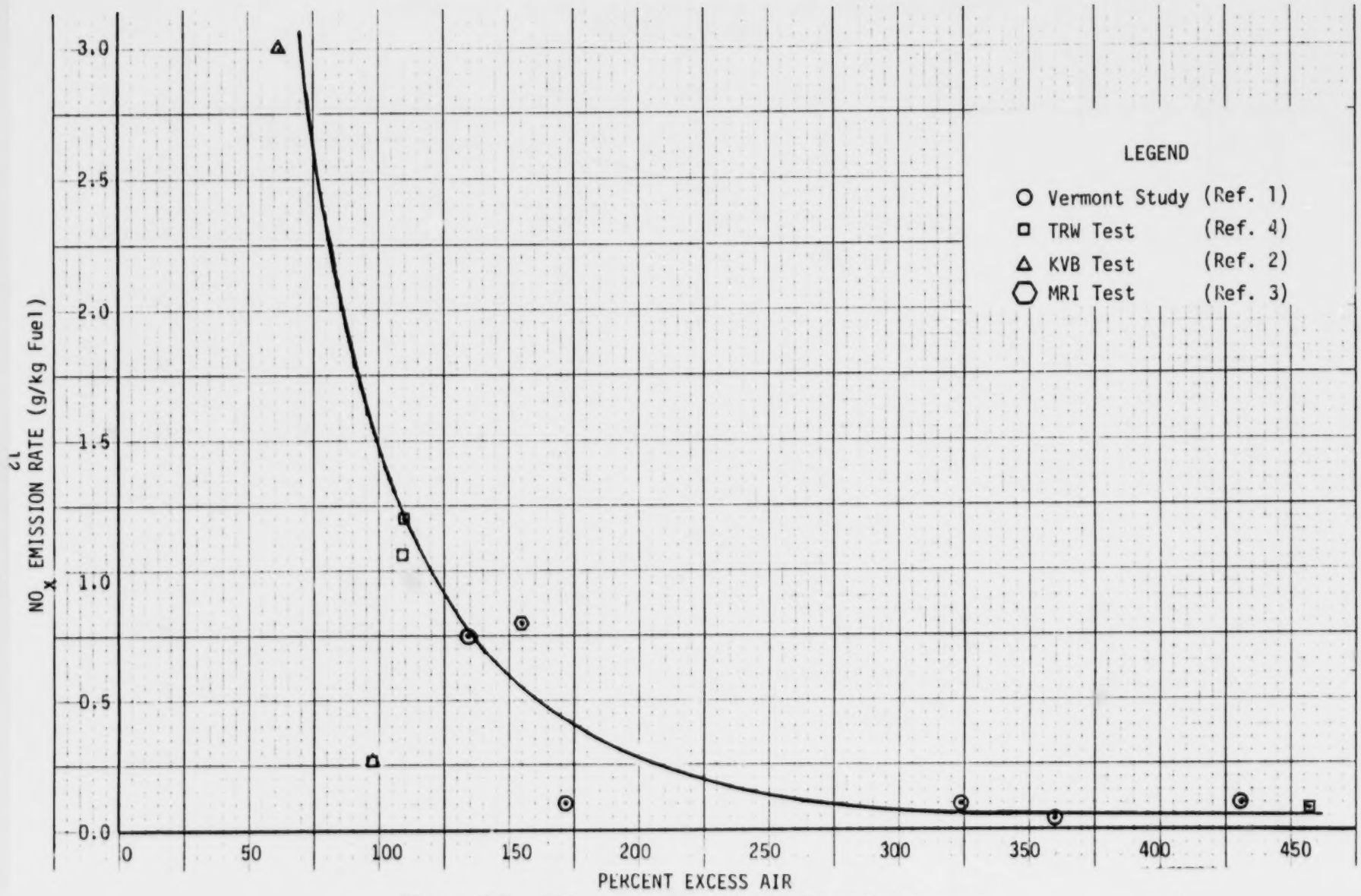

Figure 3-2. Effect of excess air on NO_x emission rate.

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

On the basis of the data reviewed, it is concluded that wood-fired boilers in the category $\leq$ 30 MW (approximately 100,000 lb steam/hr) emit considerably less NO_x (on an energy basis) than fossil fuel boilers of comparable size. For wood-fired boilers larger than 30 MW, the differential is probably not as great, but wood boilers in this size category are still expected to emit somewhat less than comparably sized fossil fuel boilers. These conclusions are based on comparison of wood boiler NO_x emission factors developed in this study to fossil fuel boiler emission factors cited in AP-42 (5).

For the range of boiler sizes studied, the NO_x emission factors were found to decrease as excess air increased. In contrast, higher levels of excess air in fossil fuel boilers are normally associated with increased NO_x emission rates. In the case of the wood boilers, it is suspected that the cooling effect of large quantities of excess air resulted in lower average firebox temperatures. This would decrease the amount of thermal NO_x formed. Thermal NO_x refers to NO_x resulting from the oxidation of molecular nitrogen (N_2) that is present as the primary molecular component of combustion air.

4.2 RECOMMENDATIONS

(1) It is recommended that NO_x emission factors for larger wood-fired boilers be established. Specifically, NO_x emissions for wood boilers in the size category > 30 MW (100,000 lb steam/hr) should be determined. Because the NO_x emission factors per unit of fuel or per unit of energy are expected to be greater for this category, this assessment is important to the NO_x/wood combustion issue.

(2) It is recommended that additional data on NO_x from bark-fired boilers be obtained. The composition and physical form of this residue fuel could result in NO_x emission rates significantly different from other wood based fuels.

(3) It is recommended that the effects of co-firing with various fossil fuels, particularly oil and gas, be investigated.

(4) It is recommended that for all future wood-boiler assessment projects, the average firebox temperature be measured. This information would help to resolve the mechanism by which more or less NO_x is formed.

(5) For the long term, it is recommended that the effects of (a) combustor design, (b) operating conditions, and (c) fuel parameters on NO_x emission rates be studied. This would lead directly to recommendations of combustion modification that would decrease NO_x emissions, if that action became necessary.

SECTION 5

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APPENDIX A

TEST DATA

TABLE A-1. BOILER A

Size of Boiler	1.5 MW (5.1 MMBtu/hr)	(150 HP)(4450 lb/hr)
Manufacturer	D. M. Dillon	
Type of Fuel	Dried and Green Shavings	
Fuel Feed Rate	363 kg/hour	(800 lb/hour)
Heat Content of Fuel	19.6×10^6 J/kg	(8440 Btu/lb)
Temperature of Fire Box	1038°C	(1900°F)
Percent Excess Air	324%	
NO_x Concentration in Exhaust Gas	1.8 ppm	
Exhaust Flow Rate	160 DSCM/min.	(5737 DSCF/min.)
Exhaust Temperature	127°C	(260°F)
Control Equipment	None	
Sampling Methodology	EPA Method 7	

	g/kg Fuel	lb/ton Fuel	$mg/10^6J$	$lb/10^6Btu$
NO_x Emission Rate	0.10	0.19	5.0	0.011

TABLE A-2. BOILER B

Size of Boiler	2.5 MW (8.5 MMBtu/hr)	(250 HP)(7,420 lb/hr)
Manufacturer	Keeler	
Type of Fuel	Oak, Maple, and Pine Shavings and Sawdust	
Fuel Feed Rate	454 kg/hour	(1000 lbs/hour)
Heat Content of Fuel	19.1 x 10^6 J/kg	(8220 Btu/lb)
Temperature of Fire Box	1038°C	(1900°F)
Percent Excess Air	534%	
NO_x Concentration in Exhaust Gas	2.6 ppm	
Exhaust Flow Rate	163 DSCM/min.	(5825 DSCF/min)
Exhaust Temperature	187°C	(368°F)
Control Equipment	Ash Collector	
Sampling Methodology	EPA Method 7	

	g/kg Fuel	lb/ton Fuel	mg/10^6J	lb/10^6Btu
NO_x Emission Rate	0.10	0.20	6.0	0.013

TABLE A-3. BOILER C

Size of Boiler	2.0 MW (6.8 MMBtu/hr)	(200 HP)(5,930 lb/hr)
Manufacturer	D. M. Dillon	
Type of Fuel	Maple Shavings and Sawdust	
Fuel Feed Rate	400 kg/hour	(880 lb/hour)
Heat Content of Fuel	19.5×10^6 J/kg	(8387 Btu/lb)
Temperature of Fire Box	1200°C	(2200°F)
Percent Excess Air	432%	
NO_x Concentration in Exhaust Gas	1.7 ppm	
Exhaust Flow Rate	194 DSCM/min.	(6911 DSCF/min.)
Exhaust Temperature	118°C	(245°F)
Control Equipment	None	
Sampling Methodology	EPA Method 7	

	g/kg Fuel	lb/ton Fuel	$mg/10^6J$	$lb/10^6Btu$
NO_x Emission Rate	0.10	0.20	5.0	0.012

TABLE A-4. BOILER D

Size of Boiler	2.5 MW (8.5 MMBtu/hr)	(257 HP)(7420 lb/hr)
Manufacturer	D. M. Dillon	
Type of Fuel	Hard and Softwood Edgings	
Fuel Feed Rate	562 Kg/hour	1240 lb/hour)
Heat Content of Fuel	19.5×10^6 J/kg	(8400 Btu/lb)
Temperature of Fire Box	1038°C	(1900°F)
Percent Excess Air	134%	
NO_x Concentration in Exhaust Gas	3.0 ppm	
Exhaust Flow Rate	137 DSCM/min.	(4878 DSCF/min.)
Exhaust Temperature	231°C	(447°F)
Control Equipment	None	
Sampling Methodology	EPA Method 7	

	g/kg Fuel	lb/ton Fuel	$mg/10^6J$	$lb/10^6Btu$
NO_x Emission Rate	0.75	1.50	38.0	0.088

TABLE A-5. BOILER E

Size of Boiler	2.9 MW (9.9 MMBtu/hr)	(300 HP)(8,500 lb/hr)
Manufacturer	Erie City	
Type of Fuel	Hard and Softwood Scraps	
Fuel Feed Rate	1170 kg/hr	(2580 lb/hour)
Heat Content of Fuel	18.7 x 10^6 J/kg	(8056 Btu/lb)
Temperature of Fire Box	1038°C	(1900°F)
Percent Excess Air	172%	
NO_x Concentration in Exhaust Gas	6.9 ppm	
Exhaust Flow Rate	177 DSCM/min.	(6306 DSCF/min.)
Exhaust Temperature	142°C	(287°F)
Control Equipment	None	
Sampling Methodology	EPA Method 7	

	g/kg Fuel	lb/ton Fuel	mg/10^6J	lb/10^6Btu
NO_x Emission Rate	0.10	0.20	6.0	0.015

TABLE A-6. BOILER F

Size of Boiler	1.5 MW (5.1 MMBtu/hr)	(150 HP)(4,450 lb/hr)
Manufacturer	D. M. Dillon	
Type of Fuel	Maple and Pine Shavings and Sawdust	
Fuel Feed Rate	300 kg/hour	(660 lb/hour)
Heat Content of Fuel	20.6 kg/hour	(8856 Btu/lb)
Temperature of Fire Box	1038°C	(1900°F)
Percent Excess Air	360%	
NO_x Concentration in Exhaust Gas	9.8 ppm	
Exhaust Flow Rate	94 DSCM/min.	(3361 DSCF/min.)
Exhaust Temperature	206°C	(403°F)
Control Equipment	None	
Sampling Methodology	EPA Method 7	

	g/kg Fuel	lb/ton Fuel	$mg/10^6J$	$lb/10^6Btu$
NO_x Emission Rate	0.04	0.07	2.0	0.004

TABLE A-7. BOILER 5

Size of Boiler	1.5 MW (5.1 MMBtu/hr)	(150 HP)(4,450 lb/hr)
Manufacturer	Will-Burt Company	
Type of Fuel	Pressed Sawdust	
Fuel Feed Rate	93 kg/hour	(205 lb/hour)
Heat Content of Fuel	19.3×10^6 J/kg	(8300 Btu/lb)
Temperature of Fire Box	NA	
Percent Excess Air	NA	
NO_x Concentration in Exhaust Gas	7.0 ppm	
Exhaust Flow Rate	5 DSCM/min.	(170 DSCF/min.)
Exhaust Temperature	84°C	(184°F)
Control Equipment	None	
Sampling Methodology	Chemiluminescence	

	g/kg Fuel	lb/ton Fuel	mg/10^6J	lb/10^6Btu
NO_x Emission Rate	0.04	0.07	2.0	0.004

TABLE A-8. BOILER H

Size of Boiler	11.6 MW (39.5 MMBtu/hr) (1,185 HP)(34,000 lb/hr)	
Manufacturer	Puget Sound Machinery	
Type of Fuel	Pine Wastewood From Sawmill	
Fuel Feed Rate	5135 kg/hour	(11,320 lb/hour)
Heat Content of Fuel	19.3 x 10^6 J/kg	(8300 Btu/lb)
Temperature of Fire Box	NA	
Percent Excess Air	110%	
NO_x Concentration in Exhaust Gas	25 ppm	
Exhaust Flow Rate	2514 DSCM/min.	(89,800 DSCF/min.)
Exhaust Temperature	68°C	(155°F)
Control Equipment	None	
Sampling Methodology	Chemiluminescence	

	g/kg Fuel	lb/ton Fuel	mg/10^6J	lb/10^6Btu
NO_x Emission Rate	1.20	2.40	60.0	0.147

TABLE A-9. BOILER I

Size of Boiler	16.8 MW (57.3 MMBtu/hr)	(1720 HP)(50,000 lb/hr)
Manufacturer	Erie City Iron Works	
Type of Fuel	Sawdust	
Fuel Feed Rate	1711 kg/hour	(17,000 lb/hour)
Heat Content of Fuel	19.3×10^6 J/kg	(8300 Btu/lb)
Temperature of Fire Box	NA	
Percent Excess Air	109%	
NO_x Concentration in Exhaust Gas	47 ppm	
Exhaust Flow Rate	1740 DSCM/min.	(62,111 DSCF/min.)
Exhaust Temperature	68°C	(155°F)
Control Equipment	None	
Sampling Methodology	Chemiluminescence	

	g/kg Fuel	lb/ton Fuel	$mg/10^6J$	$lb/10^6Btu$
NO_x Emission Rate	1.06	2.1	55.0	0.127

TABLE A-10. BOILER J

Size of Boiler	6.6 MW (22.5 MMBtu/hr)	(675 HP)(19,580 lb/hr)
Manufacturer	Wellons, Inc.	
Type of Fuel	Sawdust	
Fuel Feed Rate	1044 kg/hour	(2300 lb/hour)
Heat Content of Fuel	19.3×10^6 J/kg	(8300 Btu/lb)
Temperature of Fire Box	NA	
Percent Excess Air	457%	
NO_x Concentration in Exhaust Gas	1.8 ppm	
Exhaust Flow Rate	676 DSCM/min.	(23,868 DSCF/min.)
Exhaust Temperature	69°C	(157°F)
Control Equipment	None	
Sampling Methodology	Chemiluminescence	

	g/kg Fuel	lb/ton Fuel	$mg/10^6J$	$lb/10^6Btu$
NO_x Emission Rate	0.09	0.18	5.0	0.011

TABLE A-11. BOILER K

Size of Boiler	5.7 MW (19.4 MMBtu/hr)	(586 HP)(17,000 lb/hr)
Manufacturer	Wellons	
Type of Fuel	Sawmill Waste Wood	
Fuel Feed Rate	(1284 kg/hour)	(2830 lb/hour)
Heat Content of Fuel	19.3 x 10^6 J/kg	(8300 Btu/lb)
Temperature of Fire Box	NA	
Percent Excess Air	99%	
NO_x Concentration in Exhaust Gas	6.6 ppm	
Exhaust Flow Rate	577 DSCM/min.	(20,387 DSCF/min)
Exhaust Temperature	104°C	(219°F)
Control Equipment	None	
Sampling Methodology	Chemiluminescence	

	g/kg Fuel	lb/ton Fuel	mg/10^6J	lb/10^6Btu
NO_x Emission Rate	0.27	0.53	14.2	0.032

TABLE A-12. BOILER L

Size of Boiler	33 MW (112.6 MMBtu/hr) (3370 HP)(100,000 lb/hr)	
Manufacturer	Wickes	
Type of Fuel	80% Wood Chips/20% No. 2 Fuel Oil	
Fuel Feed Rate	8981 kg/hour	(19,800 lb/hour)
Heat Content of Fuel	24.9×10^6 J/kg	(6,766 Btu/lb)
Temperature of Fire Box	NA	
Percent Excess Air	155%	
NO_x Concentration in Exhaust Gas	66 ppm	
Exhaust Flow Rate	1252 DSCM/min.	(44,700 DSCF/min.)
Exhaust Temperature	153°C	(307°F)
Control Equipment	2 Mechanical Collectors	
Sampling Methodology	Chemiluminescence	

	g/kg Fuel	lb/ton Fuel	$mg/10^6J$	$lb/10^6Btu$
NO_x Emission Rate	0.80	1.60	50.9	0.118

TABLE A-13. BOILER M

Size of Boiler	67 MW (229 MM Btu/hr) (6868 HP)(200,000 lb/hr)
Manufacturer	B and W
Type of Fuel	85% Bark/15% Natural Gas
Fuel Feed Rate	NA
Heat Content of Fuel	19.4×10^6 J/kg (8331 Btu/lb)
Temperature of Fire Box	NA
Percent Excess Air	62%
NO_x Concentration in Exhaust Gas	184 ppm
Exhaust Flow Rate	NA
Exhaust Temperature	NA
Control Equipment	Electrostatic Precipitator
Sampling Methodology	Chemiluminescence

	g/kg Fuel	lb/ton Fuel	$mg/10^6J$	$lb/10^6Btu$
NO_x Emission Rate	NA	NA	124	0.290

TABLE A-14. BOILER N

Size of Boiler	33 MW (112.6 MMBtu/hr)	(3370 HP)(100,000 lb/hr)
Manufacturer	Wickes Boiler Company	
Type of Fuel	20% Bark/80% Coal	
Fuel Feed Rate	NA	
Heat Content of Fuel	23.8×10^6 J/kg	(10,208 Btu/lb)
Temperature of Fire Box	NA	
Percent Excess Air	92%	
NO_x Concentration in Exhaust Gas	273 ppm	
Exhaust Flow Rate	NA	
Exhaust Temperature	209°C	(409°F)
Control Equipment	Multiclone	
Sampling Methodology	Chemiluminescence	

	g/kg Fuel	lb/ton Fuel	$mg/10^6J$	$lb/10^6Btu$
NO_x Emission Rate	4.04	8.16	168	0.39